

DEVELOPMENT OF TRANSGENIC MODEL FOR INTERVENTIONS IN
NEURODEGENERATIVE DISEASES

FIELD OF THE INVENTION

[0001] This invention relates to transgenic mice for use in the study of neurodegenerative diseases.

GOVERNMENT INTEREST

[0002] The invention was made with government support from the National Institutes of Health under grant number AG10869.

BACKGROUND

[0003] Alzheimer's disease (AD), Parkinson's disease (PD) and Lewy Body disease (LBD) are the most commonly found neurodegenerative disorders in the elderly. Although their incidence continues to increase, creating a serious public health problem, to date these disorders are neither curable nor preventable. There is a genetic component to these diseases, however most cases arise spontaneously in the population in the absence of mutations. Nerve damage results from the development of protein aggregates composed of proteins normally expressed in the brain. It is not known what causes the conversion of normally non-toxic proteins to their toxic state.

[0004] Recent epidemiological studies have demonstrated a close clinical relationship between AD and PD, as about 30% of Alzheimer's patients also have PD. Compared to the rest of the aging population, patients with AD are more likely to develop concomitant PD. Furthermore, PD patients that become demented usually have developed

classical AD.

[0005] Although each neurodegenerative disease appears to have a predilection for specific brain regions and cell populations, resulting in distinct pathological pictures, PD, AD and LBD also share common pathological hallmarks. Patients with familial AD, Down syndrome and sporadic AD develop Lewy bodies on the amygdala which are the classical neuropathological hallmarks of PD. Additionally, each disease is associated with the degeneration of neurons, interneuronal synaptic connections and eventually cell death, the depletion of neurotransmitters, and abnormal accumulation of misfolded proteins, the precursors of which participate in normal central nervous system function.

[0006] Biochemical studies have confirmed the link between AD, PD and LBD. The central component of Lewy bodies is α -synuclein, also known as NACP (Non-amyloid component precursor). A proteolytic fragment of NACP, known as NAC, is a key component of amyloid plaques in AD. This suggests that α -synuclein plays a role in the pathogenesis of both AD and PD.

[0007] These findings have lead to the development of a new classification of neurodegenerative disorders denominated Lewy body disease (LBD). Patients with LBD are characterized by dementia, parkinsonism, psychiatric alterations, deposition of amyloid, and formation of Lewy bodies (LBs) with filamentous characteristics. LBs are the pathogenic hallmark of both PD and LBD. Although there are several animal models that

mimic some aspects of AD and others that mimic some aspects of PD, there are no models that combine the characteristics of AD and PD, as seen in LBD.

[0008] The neuritic plaques that are the classic pathological hallmark of AD are composed essentially of A β , a 39-43 amino acid (aa) proteolytic product of the Alzheimer's amyloid precursor protein (APP), and NAC, a 35 aa proteolytic fragment of the NACP protein. Both A β and NAC were first identified in amyloid plaques as proteolytic fragments of their full length proteins, for which the full length cDNAs were identified and cloned. The cloning of APP (Kang et al., 1987) led to a burst of research in which a number of mutations in AD were found that were associated with familial forms of AD including mutations at K670N/M671L (Swedish mutation), V717I (London mutation), V717F (Indiana mutation), presenilin 1 and presenilin 2. (Note, mutations are denoted by the wild type amino acid, the number of the amino acid at which the mutation is found and the amino acid that is found in the mutant form of the protein.) These mutations seem to alter the processing of APP preferentially to the A β_{1-42} proteolytic fragment, which has a propensity to form aggregates that are pathogenic. However, such mutations cannot account for the majority of Alzheimer's patients in whom the disease arises spontaneously.

[0009] APP is expressed abundantly in synapses under normal conditions, is well conserved across species, and has been implicated in neural plasticity, learning, and memory. APP has three alternative splice variants in which exons 7 and 8 (hAPP695), exon 8 (hAPP751) or no exons (hAPP770) are spliced out of the full length transcript. The

ratio of the three forms varies between regions of the brain and in normal vs. disease states; however, no definitive pattern of normal vs. abnormal has been determined (Rockenstein et al., 1995). It is not known what regulates the differential splicing of the transcript, but evidence suggests that splicing within neurons can be regulated by factors that influence neuronal differentiation and activity. Additionally, APP is processed into proteolytic fragments $A\beta_{39-43}$ under normal conditions. Disease results from an imbalance in the production of the fragments, biasing the overproduction of the proteolytic fragments, especially those that can initiate the formation of aggregates (i.e. $A\beta_{1-42}$).

[0010] α -Synuclein is part of a large family of proteins including β - and γ -synuclein and synoretin. As with APP, α -synuclein is expressed in the normal state in synapses and is believed to play a role in neural plasticity, learning and memory. Mutations in human (h) α -synuclein that enhance the aggregation of α -synuclein have been identified (A30P and A53T) and are associated with rare forms of autosomal dominant forms of PD. The mechanism by which these mutations increase the propensity of α -synuclein to aggregate are unknown.

[0011] Despite the fact that a number of mutations can be found in APP and α -synuclein in the population, most cases of AD and PD arise spontaneously. The most frequent sporadic forms of these diseases are associated with an abnormal accumulation of $A\beta$ and α -synuclein, respectively. However, the reasons for overaccumulation of these proteins is unknown. $A\beta$ is secreted from neurons and accumulates in extracellular

amyloid plaques. Additionally A β can be detected inside neurons. α -Synuclein accumulates in intraneuronal inclusions called Lewy bodies. Although the two proteins are typically found together in extracellular neuritic AD plaques, they are also occasionally found together in intracellular inclusions.

[0012] Studies have been performed to analyze the processing of the non-toxic precursor proteins to their toxic proteolytic products, both in tissue culture systems and using purified proteins. Aggregates may be formed in nerve cell cultures by overexpression of α -synuclein. Overexpression of wild-type APP does not cause formation of extracellular protein aggregates in culture; however, overexpression of the Swedish APP mutation, the most pathogenic of the APP mutations, does. Aggregates may also be formed in response to oxidative stress in cell culture in cells overexpressing α -synuclein, suggesting that it may be important in the development of disease. Additionally, purified A β and NAC peptides are able to form aggregates *in vitro*, either alone or mixed, under identical conditions of temperature and pH.

[0013] Attempts to establish animal models of AD, PD and LBD have been disappointing. Initially, animals expressing transgenic APP failed to show extensive AD-type neuropathology (Kammesheidt et al., 1992; Lamb et al., 1993; Mucke et al., 1994; Higgins et al., 1995; Andr    et al., 1996). This was likely due to low levels of protein expression. Games et al. (1995) were able to generate a transgenic mouse that showed some AD-type pathology due to the high level of expression of a mutant APP (V717F)

driven by a PDGF- β promoter. The transgenic animals did exhibit deposits of human A β in the hippocampus, corpus callosum and the cerebral cortex, but in no other regions of the brain. Plaques were observed, but there were no neurofibrillary tangles. The author stated that such results were expected as neurofibrillary tangles did not exist in rodents.

[0014] Transgenic mice expressing the Swedish double mutation (670/671) or the Swedish mutation in conjunction with the London mutation (V717I) under control of the Thy1 expression cassette were also generated (Sturchler-Pierrat et al., 1997). The age of development of plaques varied from 6 months to more than two years in each of the mice strains, and seemed to correlate well with expression levels of the proteins. Lower expression levels were required to induce pathological changes associated with disease in the animals carrying both the Swedish and Indiana mutations. However, neither animal was a full and accurate representation of the disease. Plaque formation accompanied by neuritic changes, dystrophic cholinergic fibers and inflammation were observed in the hippocampus and neocortex, but not in other brain regions. In a separate study using transgenic mice expressing the Swedish mutant form of APP under the PrP- promotor (Hsiao et al., 1996), mice were found to have normal learning and memory at 3 months, but showed impairment by 9 or 10 months. Plaques were observed in the cortical and limbic areas in these transgenic mice and a 14-fold increase in A $\beta_{1-42/43}$ was observed.

[0015] As A β_{1-42} was known to be one of the strongly causative factors in AD, Mucke et al. (2000) created a transgenic mouse that expressed only the toxic fragment of APP,

$A\beta_{1-42}$. Expression of the $A\beta_{1-42}$ fragment was toxic to the cells, but no plaques were formed, suggesting a plaque independent role for $A\beta_{1-42}$ in the progression of AD.

[0016] Additionally, transgenic animals expressing APP were found to display a variety of neurological problems including learning deficits, disturbed behavior and seizures. Again, the severity of neurological dysfunction seemed to be tied to the level of expression of the APP protein. Differences could also be attributed to the regions of the brain in which APP was expressed due to differences in promoters, integration into the genome, etc. As with the physiological symptoms though, neurological dysfunction in these animals resembled some aspects, but not all, of those seen in AD, PD and LBD. The lack of an animal model for the diseases was clearly not due to a lack of effort, but instead due to an inability to induce all of the changes that occur in the disease state.

[0017] The effect of the expression of the transgenic sequence was also largely dependent on the strain of mice in which the mutant gene was expressed. For example, concentrations of APP that produce plaques in outbred transgenic lines were found to be lethal in inbred FVB/N or C57BL/6J mice (Carlson, et al., 1997). Lines of FVB/N mice expressing low enough levels of APP695 to be viable were found to develop a CNS disorder that included neophobia, impaired spatial alternation, with diminished glucose utilization and astrogliosis mainly in the cerebrum (Hsiao et al., 1995). A similar syndrome is known to occur in about 20% of non-transgenic mice of the same strain, suggesting that the APP promotes a tendency already present in the strain.

[0018] Attempts were made to generate more accurate models of AD by crossing strains of transgenic mice to alter the pathology of the disease. Overexpression of the fibroblast growth factor 2 gene (FGF2) in transgenic mice overexpressing APP made APP more lethal, but did not alter the symptoms seen. Holtzman et al (2000) generated a number of bigenic mice by crossing transgenic mice expressing the V717F mutant of APP with mice expressing various forms of apolipoprotein E (apoE). The $\epsilon 4$ allele of apoE was the first genetic risk factor identified for sporadic and late-onset familial AD (FAD) (Strittmatter et al., 1993). Later the $\epsilon 3$ allele of apoE was found to be a weaker risk factor for the disease. Expression of apoE mutants, especially the $\epsilon 4$ allele, together with the V717F mutant version of APP in mice increased the development of fibrillar deposits, neuritic plaques and neuritic degradation. Similar pathological hallmarks of AD were observed in mice expressing only the V717F mutant of APP, simply at an older age. The combination of the expression of the transgenes did not change the observed pathology of the disease, simply the time frame in which the pathology was observed. Expression of the V717F mutant version of APP in an apoE^{-/-} knockout mouse resulted in an absence of neuritic degradation. This study demonstrated a clear role for ApoE in the pathology of AD, but did not provide a more accurate model of the disease than the singly transgenic mouse.

[0019] Transgenic mice expressing α -synuclein under control of the PDGF β promotor have also been generated for use as a model of PD and LBD (Masliah et al., 2000). Neuronal expression of α -synuclein resulted in the progressive accumulation of α -

synuclein and the development of inclusions in neurons in the neocortex, hippocampus and substantia nigra. Additionally electron-dense intranuclear deposits and cytoplasmic inclusions were observed. The mice demonstrated motor impairments which were associated with loss of dopaminergic terminals in the basal ganglia. However, no amyloid plaques, fibrillary tangles or cell death were observed.

[0020] A number of α -synuclein transgenic mice have also been generated. However, despite the use of different promoters (e.g. PDGF β , Thy-1) as well as the use of both wild type and mutant forms (A30P and A53T) of α -synuclein, none of the mice provide a completely accurate model of PD. As with the various APP transgenic mice, differences were seen in the amount and location of protein expressed, depending on the promoter used and the site of insertion of the transgene into the genome. For example, when expression from the $h\alpha$ -synuclein transgene was driven by the PDGF- β promotor, the expression pattern of $h\alpha$ -synuclein most closely resembled that seen in normal brain or in diffuse LBD. Expression of $h\alpha$ -synuclein using a Thy-1 promoter resulted in higher expression of the transgene in a pattern more closely resembling the pattern of expression seen in PD. Higher expression resulted in more severe pathology. Mice expressing mutant versions of $h\alpha$ -synuclein developed hallmarks of disease earlier than those expressing the wild type version of the protein. Additionally, neurological dysfunction was dependent on the regions of the brain in which the protein was expressed.

[0021] Disease states are often the result of multiple changes in the organism, rather

than a change in the expression level of a single protein or a single mutation within a gene. Although each of the transgenic animals described above had some hallmarks of AD, PD and/or LBD, none of them could serve as a complete model of any of the diseases. Not a single animal was found to have neurofibrillary tangles, a classic indicator of AD. The realization of the overlapping pathologies and occurrence of AD, PD and LBD emphasizes the need for an animal model that displays a more complete set of the pathologies and clinical manifestations of the diseases.

SUMMARY OF THE INVENTION

[0022] The invention is a transgenic mouse model with transgenes for expression of human β -amyloid peptides or hAPP and h α -synuclein. The transgenes may be wild type, mutant or truncated forms of the genes. The transgenes may be expressed under any of a number of promoters including the PDGF- β , Thy1 and prion (PrP) promoters. An intron, such as the SV40 intron, may be included in the transgene construct or the promotor, as in the case of the Thy1 promoter, the intron of the promoter may be used.

[0023] The mice of the present invention are generated by crossbreeding of mice carrying a single transgene for α -synuclein or hAPP. Applicants have generated a number of transgenic mouse lines overexpressing h α -synuclein (Masliah et al., 2000) and either wild-type or mutant forms of hAPP (Mucke et al, 2000) to elucidate the *in vivo* mechanism of amyloidogenesis in AD, PD and LBD. Additionally, there are a number of other hAPP transgenic mice available as referenced. Available mice include those expressing APP

under control of the mouse or human Thy1 promoter (Andrä et al., 1996), the PDGF- β promoter (Games et al., 1995) with or without an SV40 intron, and the PrP (Borchelt et al., 1996; Hsia et al., 1999) promoter. The mice are well studied and characterized regarding regions of the brain and time frame in which the transgenes are expressed. Bigenic mice can readily be generated by crossing two mice that overexpress either hAPP or h α -synuclein in regions of the brain most effected by AD, PD or LBD as desired. Ideally the mice crossed should carry only one copy of the transgene such that littermates expressing both, either or neither transgene can be compared to each other. Overexpression of transgenes can be detected by any of a number of methods well known to one skilled in the art including, but not limited to, ribonuclease protection assay (RPA), Western blot, immunofluorescence, or like analysis, where the signal obtained is above background cross-reactivity with mouse RNA or protein found in non-transgenic littermates.

[0024] The bigenic PDGF- β - α -synuclein-PDGF- β -hAPP mice of the invention have been shown to express high levels of APP which is properly processed into A β fragments, in addition to exhibiting extracellular amyloidosis and neurofibrillary tangles which, in an age- and brain region-specific manner, morphologically resembles senile plaques seen in AD. Expression of h α -synuclein did not seem to alter the expression of hAPP. However, there was extensive accumulation of h α -synuclein in the bigenic mice as compared to the single h α -synuclein mice.

[0025] The functional and morphological alterations in the PDGF- β - α -synuclein-

PDGF- β -hAPP bigenic mice resembled the Lewy body variant of AD. Bigenic mice developed physiological and pathological hallmarks and impaired motor function more closely resembling human disease states as compared to singly transgenic mice. The effect of the combination of the expression of both genes is synergistic. The development of fibrillary α -synuclein inclusions, never before observed in rodents, but a standard hallmark of PD and LBD, were seen. Synaptic degeneration had been observed in both of the singly transgenic mice, but never neuronal cell death, which was seen in the bigenic mice. The bigenic mice had severe deficits in learning and memory, and developed motor deficits before PDGF- β - α -synuclein singly transgenic mice which display only minor, if any motor deficiencies. The onset of motor deficits began at 6 months with the bigenic mice, rather than at 12 months as is typically seen with the PDGF- β -hAPP mice. The bigenic mice showed the most prominent age-dependent degeneration of cholinergic neurons and presynaptic terminals as compared to their singly- or non-transgenic littermates. Although synaptic degeneration was observed in the singly transgenic mice, neuronal cell death was not observed in the singly transgenic littermates. hAPP- α -synuclein mice also had abundant β -amyloid plaques and an even greater number of α -synuclein-immunoreactive neuronal inclusions. Ultrastructurally, these inclusions were often fibrillar in double transgenic mice, but were amorphous in singly transgenic α -synuclein mice. This is the first demonstration of the presence of fibrillary Lewy-body like inclusions that were previously believed to not exist in rodents.

[0026] Additionally, the present invention is a method for the evaluation of the *in vivo*

effects of α -synuclein with APP, in combination, on amyloidogenesis and neurodegeneration. Evaluation of the effects of the proteins in the development and progression of disease may be assessed by functional, pathological or biochemical assays, ideally in comparison to littermates carrying only a single or no transgene for either α -synuclein or hAPP. Studies with bigenic α -synuclein-hAPP mice demonstrate that h α -synuclein and hAPP/A β have distinct, as well as overlapping, pathogenic effects on the integrity and function of the brain. While h α -synuclein did not affect the A β -dependent development of neuritic plaques or the overall A β content in the brain, it worsened hAPP/A β -dependent cognitive deficits and neurodegeneration in specific brain regions. These findings indicate that h α -synuclein can enhance the toxicity of A β through plaque-independent mechanisms. They correlate well with clinical observations suggesting that people with the Lewy body variant of AD have a more rapid cognitive decline than people with pure AD. Overexpression of hAPP/A β , in turn, promoted the intraneuronal accumulation of h α -synuclein in transgenic mice and accelerated the development of motor deficits. In view of these pathogenic interactions between A β and h α -synuclein, drugs aimed at blocking the accumulation of A β or h α -synuclein will likely benefit a broader spectrum of neurodegenerative disorders than previously anticipated. Additionally, the bigenic mouse provides a better predictive model of the potential for an intervention to be useful to a patient.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] **FIGURE 1.** Characterization of the motor deficits in the hSYN and the hAPP

tg mice in the rotorod. Compared to non-transgenic littermates, singly -tg hSYN mice displayed significant motor deficits. Similarly, bigenic hSYN/hAPP mice showed levels of performance impairment similar to singly-tg hSYN mice. Mice expressing hAPP alone were not different from non-tg controls. N=6-8 per genotype, age 12 months.

[0028] FIGURE 2. RNase protection assay of total RNA from brains of transgenic and non-transgenic mice. Lane U represents undigested transcripts. The right hand side notation of the figure indicate the size of the digested samples. Sample lanes represent analysis of three separate mice each from Non-Tg, non-transgenic mice (i.e. control); Thy1-hAPPtg, transgenic mice; Thy1- α -syn'tg, transgenic mice; and double tg, transgenic mice containing both the human (h)APP751 and the α -synuclein genes.

DETAILED DESCRIPTION AND PREFERRED EMBODIMENTS

[0029] The mechanisms by which altered expression and processing of α -synuclein or APP might lead to neurodegenerative disorders such as AD, PD and LBD remain somewhat unclear. It is generally understood that abnormal protein aggregation is a common feature in these disorders and that either full length α -synuclein, or protein fragments thereof, and A β are major constituents of these protein aggregates. In many disease states, multiple changes are required for the full onset of the condition. No animal models with single mutations in either APP or α -synuclein have provided accurate models of AD, PD or LBD. However, the bigenic PDGF- β - α -synuclein-PDGF- β -hAPP mouse displays hallmarks of these diseases that were not previously observed in either of the

singly transgenic animals. By expressing both proteins, one gets a more accurate model of the disease. By using mice that express different levels of each protein, one can obtain a variety of models with different rates of onset and severity of disease. These will mimic the differences seen in humans.

[0030] Transgenic mice expressing hAPP or α -synuclein can be divided into two general categories of low expressing and high expressing strains. The classes can be further subdivided into mice that express wild type proteins that are less toxic than mutant proteins. For example, all mice expressing APP will eventually develop some plaques and some disease. However, the rate of development of plaques and resulting disease will be most rapid with mice expressing the Swedish double mutation at aa 670/671. Expression of hAPP with a single mutation at aa 717 will result in disease with fewer plaques in age matched animals. Similarly, different mutations and promoters will manifest various severity of disease in α -synuclein transgenic mice. Mice expressing h α -synuclein under the control of a Thy-1 promoter accumulate protein in the synapses and neurons throughout the brain, including the thalamus, basal ganglia, substantia nigra and brainstem. One line of mice expressing α -synuclein under the control of the PDGF- β promoter accumulate protein in synapses in the neocortex, limbic system and olfactory regions, as well as in inclusion bodies in neurons in deeper layers of the neurocortex. Another strain displayed α -synuclein expression in glial cells mimicking multiple system atrophy.

[0031] In order for the proteins to act synergistically to produce pathologies not seen

in the singly transgenic mice, strains of mice that express the proteins in the same brain regions need to be mated. The production of $A\beta_{1-42}$ is clearly the driving force in the development of the LBD-like state in the bigenic mice. Expression of hAPP increases the accumulation of α -synuclein. It also increases the severity of the disease and results in an earlier age of disease onset in the α -synuclein transgenic mice. α -Synuclein transgenic mice with no apparent disease develop disease upon crossing the mice with transgenic mice expressing an amyloidogenic version of APP. Crossing α -synuclein mice with no apparent disease with mice expressing a non-amyloidogenic version of hAPP does not exacerbate the process of the development of disease. As spontaneous forms of AD, PD and LBD tend to have a relatively slow onset, suggesting low levels of mutant protein expression, crossing two strains that do not show significant disease alone provides a model for spontaneous onset of the diseases frequently seen in humans. Similarly, transgenic animals expressing APP at an earlier stage than α -synuclein mimic AD patients who later become demented. Transgenic animals expressing low levels of both proteins mimic spontaneous onset of the disease, which is slow in AD, PD and LBD. Brain regions of expression also serve as a motivation to cross specific transgenic strains. For example, mice expressing hAPP and α -synuclein in regions of the brain most severely effected in LBD could be crossed to serve as a model for LBD.

[0032] Existing transgenic mice are selected based on criteria including level and brain region of protein expression, age of development of symptoms, neurological disorders and effect of background strain. Unlike transgenic mice that are generated by

the insertion of constructs into mouse embryos that can result in a number of phenotypes, the mice of the invention are bigenic mice generated by the combination of mice with well known characteristics. Models are designed to most closely fit the disease of interest based on the criteria among those listed above. The expression of one protein is not disrupted by the expression of the other. The enhancement of the pathology of α -synuclein by co-expression of hAPP is now known. One skilled in the art may make rational decisions in combining known strains of mice to develop bigenic strains that most closely mimic the disease state of interest.

EXAMPLE 1

[0033] *Generation of transgenic α -synuclein and hAPP mice.* Transgenic mice are achieved routinely in the art using the technique of microinjection, as described in U.S. Patent No. 4,736,866 issued to Leder *et al.*, and as provided by B. Hogan *et al.* (1986). U.S. Patent 5,574,206 issued to Jolicoeur particularly describes the creation of transgenic mice bearing functional HIV genes and their use in the modeling and study of HIV-mediated diseases. These references are herein incorporated by reference.

EXAMPLE 2

[0034] *Coexpression of h α -synuclein and hAPP in vivo.* Transgenic mice in which neuronal expression of h α -synuclein (Masliah *et al.*, 2000) or FAD-mutant hAPP (Mucke *et al.*, 2000) is directed by the PDGF β chain promoter have been described. Additionally, a number of other APP mice have been described including, but not limited to, those described in the present application. Lines with high levels of neuronal h α -synuclein (line D) or A β (line J9) production were selected. Crosses between heterozygous h α -synuclein

and heterozygous hAPP mice from these lines yielded four groups of littermates: h α -synuclein mice ($n = 26$), hAPP mice ($n = 32$), h α -synuclein/hAPP mice ($n = 21$), and nontransgenic controls ($n = 31$). Levels of transgene-derived mRNAs in the brain were similar in singly and doubly transgenic mice, indicating that coexpression of h α -synuclein and hAPP did not alter transgene expression (Figure 2). At the protein level, expression of h α -synuclein did not affect hAPP expression in doubly transgenic mice. However, there was a trend for cerebral h α -synuclein levels to be higher in h α -synuclein/hAPP mice than in h α -synuclein mice, which may reflect effects of A β on h α -synuclein accumulation.

EXAMPLE 3

[0035] *Overexpression of human α -synuclein in bigenic mice enhances Alzheimer's disease-like neuropathology.* It has been established that both α -synuclein and NAC are integral components of plaques formed in *in vitro* models of Alzheimer's disease. In order to determine how these molecules contribute to amyloidogenesis *in vivo*, specifically in the PDAPP bigenic mouse models, brain sections from effected bigenic mice were treated with formic acid and immunostained with antibodies against α -synuclein and NAC. The analysis of results confirm that, as in *in vitro* models of Alzheimer's disease, in the PDAPP bigenic mice, NAC is present in the amyloid core while α -synuclein is found in the dystrophic neurites. Additionally, neuropathological examination of PDAPP bigenic mice overexpressing α -synuclein revealed widespread astrogliosis in the neocortex and hippocampus accompanied by increased amyloid deposition, once again establishing that the increased expression of α -synuclein plays a key role in the pathogenesis of

neurodegenerative conditions associated with amyloidogenesis. Therefore it was conclusively demonstrated that α -synuclein is critical for plaque formation *in vivo* and as such, constitutes a reasonable target for the design of anti-amyloidogenic compounds useful for *in vivo* therapies of Alzheimer's disease and other neurodegenerative conditions involving amyloid formation.

EXAMPLE 4

[0036] *Neurological deficits in h α -synuclein/hAPP mice.* Motor deficits were assessed with the rotarod test (FIG. 1). Consistent with previous observations, h α -synuclein mice developed age-dependent motor deficits. At 6 months of age, h α -synuclein/hAPP mice already showed deficits relative to nontransgenic controls ($P < 0.03$ by repeated measures ANOVA), whereas h α -synuclein mice still performed normally. At 12 months of age, both h α -synuclein and h α -synuclein/hAPP mice showed deficits in this test compared with nontransgenic controls ($P < 0.001$ by repeated measures ANOVA). hAPP mice had no significant motor deficits at either age. The severity of motor deficits was similar in 6-month-old h α -synuclein/hAPP and 12-month-old h α -synuclein and h α -synuclein/hAPP mice, suggesting that hAPP/A β accelerates the development of h α -synuclein-dependent motor deficits.

[0037] PDGF-hAPP mice have previously been shown to develop cognitive deficits. To determine the effects of h α -synuclein and hAPP/A β on spatial learning and memory, mice were assessed in a water maze test (Morris, 1984). In the sessions during which the

target platform was visible, all groups of mice were able to locate the platform equally well, indicating that the motor deficits of h α -synuclein/hAPP do not preclude normal performance in the water maze test. In the hidden platform sessions, mice have to use their memory of the spatial relationship of the platform to visual cues outside of the maze to locate the submerged platform. In these sessions, h α -synuclein/hAPP mice showed the most significant learning deficits, whereas h α -synuclein mice and nontransgenic controls performed normally. hAPP mice tended to perform better than h α -synuclein/hAPP mice in the hidden platform sessions, but the difference was not statistically significant. The probe trial during which the platform is removed provides a putative measure of spatial memory retention. In the probe trial, h α -synuclein/hAPP mice and hAPP mice showed significantly less preference for the target quadrant than nontransgenic controls, suggesting impaired memory retention, whereas h α -synuclein mice were not impaired.

[0038] These results indicate that the motor deficits of h α -synuclein/hAPP mice are caused primarily by h α -synuclein, whereas their deficits in spatial learning and memory are caused primarily by hAPP/A β . Similar effects of h α -synuclein and hAPP/Ab may contribute to Lewy body diseases, which also combine motor and cognitive deficits.

EXAMPLE 5

[0039] *Age-dependent neurodegeneration.* Degeneration of cholinergic neurons in the nucleus basalis of Meynert results in major acquisition deficits in the water maze task in rodents. It is also a potentially important determinant of cognitive decline in AD and

Lewy body diseases. Choline acetyltransferase (ChAT) mediates the synthesis of acetylcholine and serves as a marker of cholinergic neurons. The density of ChAT-immunoreactive neurons in the nucleus basalis of the transgenic models ($n = 12\text{--}13$ mice/genotype, age range: 4–20 months) were determined. In $\text{h}\alpha$ -synuclein/hAPP mice, simple regression analysis revealed a highly significant inverse correlation between aging and the number of cholinergic neurons ($R = 0.828$, $P = 0.0005$). A trend toward such a correlation was present also in $\text{h}\alpha$ -synuclein mice ($R = 0.538$, $P = 0.071$) and hAPP mice ($R = 0.511$, $P = 0.089$), but not in nontransgenic controls ($R = 0.127$, $P = 0.695$). The greatest loss of cholinergic neurons was observed in $\text{h}\alpha$ -synuclein/hAPP mice, while more moderate losses were found in aged hAPP mice. These results are consistent with the observation that cholinergic deficits are more severe in human cases with the Lewy body variant of AD than in cases with pure AD. $\text{h}\alpha$ -Synuclein/hAPP mice and hAPP mice also had a significant loss of cholinergic neurons in the caudate/putamen, consistent with the decreased ChAT activity in the caudate of AD patients with or without Lewy bodies.

[0040] People with AD or the Lewy body variant of AD typically also develop a significant loss of synapses in the neocortex, which is reflected in decreased synaptophysin immunoreactivity. Synaptophysin-immunoreactive presynaptic terminals of defined signal intensity (SIPT) in the neocortex of 4- to 20-month-old mice ($n = 15\text{--}19$ /genotype) were measured. There was a significant inverse correlation between aging and neocortical SIPT levels in hAPP mice ($R = 0.744$, $P = 0.0006$) and $\text{h}\alpha$ -synuclein/hAPP mice ($R = 0.524$, $P = 0.021$), but not in $\text{h}\alpha$ -synuclein mice ($R = 0.479$, P

= 0.071) or nontransgenic controls ($R = 0.151$, $P = 0.564$). At 20 months of age, SIPT levels in the neocortex (% area occupied, mean \pm SD, $n = 3-4$ mice/genotype) were highest in nontransgenic controls (25.6 ± 0.9) and lowest in α -synuclein/hAPP mice (18.3 ± 4.8 , $P < 0.05$ by Tukey-Kramer test), with values for hAPP mice (20.9 ± 1.7) and α -synuclein mice (23.0 ± 0.9) falling in between. In contrast, SIPT levels in the caudate/putamen at 20 months of age (mean \pm SD, $n = 3-4$ mice/genotype) were normal in nontransgenic mice (27.1 ± 1.5) and hAPP mice (25.1 ± 3.6), but decreased in α -synuclein mice (21.0 ± 0.9) and α -synuclein/hAPP mice (20.1 ± 1.7) ($P < 0.05$ vs nontransgenic controls by Tukey-Kramer test).

[0041] These results suggest that the age-dependent loss of cholinergic neurons in α -synuclein/hAPP mice depends primarily on hAPP/A β , with α -synuclein having some additive effects in the nucleus basalis. The age-dependent loss of SIPT in the neocortex of these mice is also due primarily to hAPP/A β with minor contributions from α -synuclein, whereas the loss of SIPT in the basal ganglia is due almost entirely to α -synuclein.

EXAMPLE 6

[0042] *A β promotes accumulation of α -synuclein.* Accumulation of α -synuclein within neurons is a hallmark of Lewy body diseases, including the Lewy body variant of AD. Age-dependent accumulation of α -synuclein in neurons of α -synuclein singly transgenic mice has been previously observed (Masliah, 2000). Between 4 and 20 months of age, the number of neuronal inclusions in the neocortex was on average 1.6-fold higher in α -

synuclein/hAPP mice than in age-matched h α -synuclein mice (15.3 ± 1.1 vs. 9.5 ± 0.9 per mm², mean \pm SEM, $P = 0.0002$ by unpaired two-tailed Student's t test, $n = 28$ – 32 mice/genotype). This is illustrated for 12-month-old mice. The number of inclusions increased with age in both h α -synuclein and h α -synuclein/hAPP mice. These results indicate that hAPP/A β enhances the accumulation of h α -synuclein in neurons.

[0043] By ultrastructural analysis, all intraneuronal inclusions in h α -synuclein mice were amorphous and electrodense, whereas many of the intraneuronal inclusions in h α -synuclein/hAPP were fibrillar, increasing their resemblance to Lewy bodies in the human disease, which typically contain fibrillar elements. The filamentous inclusions in the neuronal cytoplasm were decorated with gold particles when brain sections of h α -synuclein/hAPP mice were analyzed by immunogold electron microscopy with anti-h α -synuclein or anti-A β . These results suggest that A β may promote the *in vivo* fibrillization of h α -synuclein by direct interaction. Further supporting this possibility, A β -immunoreactive granular deposits were detected by confocal microscopy in h α -synuclein-positive intraneuronal inclusions in h α -synuclein/hAPP mice.

[0044] To further evaluate whether the alterations observed in h α -synuclein/hAPP mice could indeed result from direct pathogenetic interactions between A β and h α -synuclein, *in vivo* analysis was extended to two *in vitro* models. In a cell-free system, both freshly solubilized and putatively aggregated (aged) human A β_{1-42} strongly promoted the formation of high molecular weight polymers of h α -synuclein, consistent with previous

observations. In contrast, the less fibrillogenic $A\beta_{1-40}$ did not affect α -synuclein aggregation *in vitro*. Notably, $A\beta_{1-42}$ and $A\beta_{1-40}$ also differed in their effect on the intracellular accumulation of α -synuclein in neuronal cell cultures when added to the culture medium. $A\beta_{1-42}$ strongly increased the intracellular accumulation of α -synuclein, but $A\beta_{1-40}$ did not.

[0045] Overproduction of $A\beta_{1-42}$ within the endoplasmic reticulum and intermediate compartment may interfere with the processing of α -synuclein enhancing its accumulation. However, cell culture data demonstrate that extracellular exposure to $A\beta_{1-42}$ is sufficient to induce the intracellular accumulation of α -synuclein, whereas exposure to $A\beta_{1-40}$ is not. It is interesting in this context that incubation of cells with extracellular $A\beta_{1-42}$ disrupted the integrity of lysosomal membranes, whereas incubation of cells with $A\beta_{1-40}$ did not. Moreover, the association of soluble α -synuclein with planar lipid bilayers results in extensive bilayer disruption. The combined action of $A\beta_{1-42}$ and α -synuclein results in a leakiness of endosomal-lysosomal membranes, allowing for a direct interaction between $A\beta_{1-42}$ and α -synuclein in the cytosol. Such an interaction would promote the intracellular accumulation of α -synuclein. This effect of $A\beta_{1-42}$ on α -synuclein is likely mediated by direct fibrillogenic interactions between these molecules or by free radicals. $A\beta$ exerts oxidative stress and studies indicate that oxidative cross-linking of α -synuclein contributes to the formation of Lewy bodies (Hashimoto et al., 1999; Lee et al., 2000).

[0046] In contrast to the prominent effects of hAPP/ $A\beta$ on α -synuclein-associated

pathology, h α -synuclein expression did not significantly alter the extracellular deposition of A β into plaques or the development of plaque-associated neuritic dystrophy in 8-, 12-, and 20-month-old h α -synuclein/hAPP mice compared with age-matched hAPP mice ($n = 3-4$ mice per genotype and age). Twelve-month-old hAPP and h α -synuclein/hAPP mice had similar cerebral levels of A β_{1-40} (4.3 ± 0.88 vs 4.6 ± 0.6) and A β_{1-42} (248 ± 48 vs 275 ± 41) as determined by ELISA (mg/g of hemibrain, mean \pm SD, $n = 4-11$ mice/genotype).

EXAMPLE 7

[0047] Total RNA from hemibrains or from dissected brain regions was isolated and then analyzed by a solution hybridization RNase protection assay and resolved on a acrylamide/urea/Tris/borate/EDTA gel (Figure 2). Lane U represents undigested transcripts of the α -synuclein gene (α -syn), the A β precursor gene (APP) and actin (actin). The right hand side notation of the figure indicate the size of the digested samples. Sample lanes represent analysis of three separate mice each from Non-Tg, non-transgenic mice (i.e. control); Thy1-hAPPtg, transgenic mice expressing human (h)APP751 cDNA under the regulatory control of the murine (m)Thy-1 gene; They1- α -syn'tg, transgenic mice expressing human α -synuclein under the regulatory control of the muring (m)Thy-1 gene; and double tg, transgenic mice containing both the human (h)APP751 and the α -synuclein genes under the regulatory control of the murine (m)Thy-1 gene.

EXAMPLE 8

[0048] *Crossbreeding of h α -synuclein or PDAPP-J9M tg mice with m α - or m β -synuclein KO mice.* To further confirm that the deletion of α -synuclein will result in suppression of A β deposits in bigenic mice, whereas, deletion of β -synuclein will result in the stimulation of A β deposits, knock out (KO) mice, having the genes encoding α -synuclein or β -synuclein deleted (Lexicon Genetics Inc., The Woodlands, TX) were crossed with heterozygous PDAPP-J9M tg mice. The following lines were generated: 1) (PDAPP^{-/-};m α -syn^{+/+}), 2) (PDAPP^{-/-};m α -syn^{+/-}), 3) (PDAPP^{+/-};m α -syn^{+/+}), 4) (PDAPP^{+/-}; m α -syn^{+/-}), and 5) (PDAPP^{-/-}; m α -syn^{-/-}). Mouse genotype was determined by PCR using tail DNA. Subsequently, the (PDAPP^{+/-};m α -syn^{+/-}) were intercrossed generating the following offspring: 1) (PDAPP^{+/+};m α -syn^{+/+}), 2) (PDAPP^{+/+};m α -syn^{+/-}), and 3) (PDAPP^{+/+};m α -syn^{-/-}). The same breeding protocol was followed for the generation of bigenic h α -synuclein or PDAPP-J9M and m β -synuclein KO mice.

[0049] The effect of α -synuclein and β -synuclein on amyloid deposition was evaluated in both the homozygous KO mice (PDAPP^{+/+};m α -syn^{-/-}) and in the mice hemizygous for synuclein (PDAPP^{+/+};m α -syn^{+/-}) utilizing the same rotorod and neuropathological analysis used in previous examples.

EXAMPLE 9

[0050] *Crossbreeding of h α -synuclein or PDAPP-J9M tg mice with mice*

overexpressing *h* β -synuclein. Following standard crossbreeding protocol (Mucke et al., 1995), the contents of which are herein incorporated by reference, high expressor heterozygous β -synuclein mice were crossed with heterozygous α -synuclein or PDAPP-J9M tg mice resulting in the generation of : 1) non-tg littermates (PDAPP^{-/-}; h α or β syn^{-/-}), 2) bigenic (PDAPP^{+/-} and h β -synuclein^{+/-}), 3) bigenic (h α -synuclein ^{+/-} and h β -synuclein ^{+/-}), 4) singly tg hAPP, and 5) singly tg h α -synuclein or β -synuclein. Mouse genotype was confirmed using PCR with tail DNA.

[0051] Because the original line of α -synuclein tg mice showed motor deficits when subjected to the rotorod, the bigenic crosses were evaluated in the same manner. Analysis of rotorod performance revealed that β -synuclein overexpression reduced the motor deficits in α -synuclein tg mice. Subsequent neuropathological analysis demonstrated that β -synuclein overexpression resulted in the reduction of neuronal inclusions. β -synuclein overexpression was also shown to result in the reduction of neuronal loss in the α -synuclein tg mice. These results further confirm that β -synuclein is active *in vivo* and that it constitutes a substance that has potential as an anti-Parkinsonian and anti-Alzheimer's therapeutic.

[0052] h α -Synuclein/hAPP bigenic mice have cognitive and motor alterations, loss of cholinergic neurons and SIPT, extensive amyloid plaques, and h α -synuclein-immunoreactive intraneuronal fibrillar inclusions. All of these features are also found in the Lewy body variant of AD. Collectively, Lewy body diseases are common

neurodegenerative disorders, second only to AD. They comprise a heterogeneous group of diseases including PD, diffuse Lewy body disease, and the Lewy body variant of AD. Patients with Lewy body disease typically have Lewy bodies, parkinsonism and cognitive impairments. Approximately 25% of patients with AD develop frank parkinsonism, and α -synuclein-immunoreactive Lewy body-like inclusions develop in most cases of sporadic AD and FAD, as well as in Down's syndrome, which is associated with early-onset AD. Moreover, Lewy bodies contain hAPP. These associations indicate that hAPP/A β plays a role in the formation of Lewy bodies and the development of Lewy body diseases.

[0053] Studies with the hAPP/ α -synuclein mice demonstrate that α -synuclein and hAPP/Ab have distinct, as well as convergent, pathogenic effects on the integrity and function of the brain. While α -synuclein did not affect the A β -dependent development of neuritic plaques or the overall A β content in the brain, it worsened hAPP/A β -dependent cognitive deficits and neurodegeneration in specific brain regions. These findings indicate that α -synuclein enhances the toxicity of A β through plaque-independent mechanisms. These data explain clinical observations suggesting that people with the Lewy body variant of AD have a more rapid cognitive decline than people with pure AD. Overexpression of hAPP/A β , in turn, promoted the intraneuronal accumulation of α -synuclein in transgenic mice and accelerated the development of motor deficits. These effects were most likely mediated by A β or another hAPP product, *in vitro* studies indicate that A β is the culprit. In view of these pathogenic

interactions between A β and h α -synuclein, drugs aimed at blocking the accumulation of Ab or h α -synuclein will benefit a broader spectrum of neurodegenerative disorders than previously anticipated.

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What is claimed is: